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Bernstein's Last Paper: The Immediate Tasks of Neurophysiology in the Light of the Modern Theory of Biological Activity

Onno G. Meijer and Rob Bongaardt

In August 1966, the city of Moscow hosted the Eighteenth International Congress of Psychology. Anochin (cf. Pickenhain, 1988) had prepared a symposium on Cybernetic Aspects of Integrative Brain Activities, for which N.A. Bernstein was invited to present a paper: The immediate tasks of neurophysiology in the light of the modern theory of biological activity. Bernstein died just before the conference, but the Russian original and English translation of his paper survived.

For several reasons, this 1966 paper is interesting for an international audience even today. The paper reveals the heuristic that was so typical of Bernstein (Bongaardt & Meijer, in press); that is, he always moved one step beyond the leading edge of movement science. Bernstein's earlier work on coordination (1935/1967) is frequently cited (Feigenberg & Latash, 1996), but in the 60s he focused on his "physiology of activity," which yet awaits general recognition. Bernstein's parting message was that the physiology of activity needs a naturalistic theory of "display." If one realizes that the modeling of pattern recognition and pattern control continues to form problems that are hard to tackle, one may conclude that Bernstein's work remained on top of the issues up to the very end of his life. Although dated, the content of Bernstein's 1966 paper is relevant to contemporary movement science.

The text is given "as is"—a list of points to be presented at the conference rather than a complete paper, although the translation has been edited for clarity. We introduce the text by sketching the development of Bernstein's physiology of activity until the 1966 paper. Endnotes provide historical content and clarify particular points in the text.

Bernstein's Physiology of Activity

Nicholai Aleksandrovitch Bernstein (1896–1966) entered the study of movement through his fascination with the brain (Bongaardt & Meijer, in press). His famous 1935 paper carries the title "The Problem of Interrelation Between Coordination and Localization" (1935/1967), and in it he argued that coordination consists of relationships between kinematic degrees of freedom. In Bernstein's view, this fact

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points to a type of brain organization that is characterized by relationships. During the next 10 years, he focused on this intertwining of movement coordination and neurophysiology (e.g., Bernstein, 1940/1967, 1947/1988).

In his popular 1947 "On Dexterity and Its Development" (1947/1996), Bernstein again took a step ahead, focusing on the characteristic ability of higher animals to deal with unexpected motor problems by taking immediate, often unique action. Such dexterity, he argued, is only found in animals with a well-developed cortex, which allows them to assess the present situation, plan their actions ahead, and learn from their experience. The examples Bernstein provided, such as prey outsmarting its predator, belong to everyday life. Scientifically, however, he entered uncharted territory in that he started to develop a nondualistic, naturalistic theory that explains how the cortex leads to unlearned goal-directed behavior. This theory he coined the "physiology of activity" (e.g., Bernstein, 1961/1967; 1965/1988; the present paper). Lev Latash (personal communication) explained that the Russian word *aktivnost*, borrowed from Vygotsky (1926/1994; cf. Bongaardt, 1996), is better translated as *initiative*. Contrary to the Pavlovian theory of the reactive animal (Pavlov, 1927), Bernstein aimed at a brain physiology of how animals take the initiative. Within that physiology, he came to regard coordination as a mere technical aspect of the execution of movements (Bernstein, 1957/1967).

During the 60s, definite progress was made in the physiology of activity. Given that regulation in higher animals often depends on extrapolation of gradients, Bernstein (1961/1967) concluded that the planning of movements must depend on stochastic extrapolation of the past–present. The crucial question thereby was how organisms select a specific gradient in order to solve a motor problem. Bernstein became involved in the work of Gelfand and Tsetlin (1962) and adopted their mathematics of search behavior. For the solution of motor problems, the organism must distinguish between essential variables and nonessential variables (Bernstein, 1962/1967). Initiative entails that a new essential variable, specifying the solution to a motor problem, is found by stochastic, nonlocal "long jumps" in the search space. The corresponding nonessential variables then take care of local adaptations. A general mathematics of initiative thus took shape. And a new set of problems announced itself.

The Immediate Tasks of Neurophysiology in the Light of the Modern Theory of Biological Activity[1,2]

Nicholai A. Bernstein

1.[3] The organs of motion of human beings (and higher animals) possess extraordinarily great redundancy in degrees of freedom of mobility, which allows them to carry out numerous programs with the help of these organs. However, in every case, processes of coordination are necessary because of the same redundancy; these processes are defined as overcoming redundant degrees of freedom of a moving organ, that is, its transformation into a controlled system.

2. The need to possess the function and apparatus of control is dictated also by a crucially important dynamic reason in addition to the above-mentioned kine-

matic reason. The forces that need to be overcome in every realized act are vector sums of the external, reactive and, notably, internal muscular forces in every moving link. Only the third component is provided by and dependent upon the organism. However, the muscular force or moment is the function of two variables: (a) the mechanical measure of excitation and (b) the length of muscle and the speed of its change; that is, the dependence of torque on effector command is not simple. All the above-mentioned facts require a ring block diagram of movement control (reflex ring) with a continuous circular flux of information. The afferent systems of the ring are based upon hierarchically organized sensory syntheses and carry out sensory regulation of the motor act, bringing it into accord with the principal goal of the movement and adapting the designed program and composition of the motor act to required values.[4]

3.[5] The projection[6] of action and the control as a means of realizing this action are possible, but they are necessary only in those systems that can simulate the future with the help of models (code): (a) extrapolate probable future and (b) create goals for achieving required future. Such systems are found only in biological (living) objects and, in part, in artificial systems created in recent years following the design of biological systems.

4. The main psychophysiological category in all possible manifestations of vital activity, both in onto- and morphogenesis, and in all forms of interaction of the living organism with the environment, is the category of activity. Among the large number of processes of vital activity of an organism, this category of activity manifests itself most clearly in motor acts, since they represent almost the only and, in any case, the main function, with the help of which the organism not only interacts with the environment but also exerts active influence upon it, trying to change the environment according to its needs.

5.[7] As follows from the above, the classical conception of reflex as the most important element of vital activity, and the interpretation of stimulus and reaction to it in terms of cause and effect, which was convenient for adherents of the mechanical conception of functional mosaic[8] because of its resemblance to determinism, must be rejected presently as only a first rough approximation to reality. This interpretation did not take into account the most important factors, which were pushed into the background by adherents of the classical reflex conception. Without arguing that the external stimulus causes the emergence of a reflex, the modern physiological theory puts main emphasis on the fact that an organism's reaction to a stimulus (both unconditioned and conditioned reaction), in its form and content, is determined not by the stimulus itself but by its significance for the individual; that is, the most important role is played by factors of internal purposefulness, against the background of which an external stimulus is frequently reduced to a trigger signal. In actions saturated with meaning and internal content (so-called spontaneous actions[9]), such a trigger signal may be completely absent.

6. The significance of the concept of reflex is greatly reduced when one tries to comprehend its cause–effect relationship, which puts the organism in a position of a semiautomatic machine completely driven by the environment ("in equilibrium"[10]). The unquestionably greater correctness of the scheme of the reflex ring as compared with the old comprehension of reflex as an open arc invalidated the interpretation of reflexes as elementary "little bricks" of which the actions of any degree of complexity are made in chain summation. The process along the living reflex ring cannot be broken by its nature and is not amenable to decom-

position into any mosaics of elements. All the facts from modern behavioral science mean that any reflex (in the narrow "classical" sense of the word) is not the element of an action, but an elementary action as integral as any other action.

7.[11] The cardinal premise for physiological (and general biological) activity is the ability to make prognoses and model the future, the study of which, in all its aspects, is presently on the order of the day. First of all, one should note that programming every manifestation of activity directed at solving a model-shaped problem requires the organism to subdivide clearly the parameters included in the composition of the program into two categories, which are distinctly different from each other both in the characteristics of these programs and also in the position taken by the organism toward them. The parameters of these categories can be termed as essential variables and nonessential variables, respectively. The first group of parameters are characterized mainly by qualitative features (in motor acts—by topological features) and by discrete numbers (the shape of the leaf of a tree, the number of vertebrae, teeth, stamens of a flower, the main features of an image, motor habit, and so forth); the second group of parameters are characterized by the more or less wide continuous spread and stochastic structure. The differences in the attitude of the organism toward the parameters of either category are also strongly pronounced. In realizing the parameters of the category of essential variables, the organism is clearly characterized by the negative entropy.

The organism tries to realize the essential variables by completely overcoming any difficulties and influences from the environment; as for the parameters of nonessential variables, the organism, on the contrary, is yieldingly adaptable. In short, the organism is active toward the former and reactive toward the latter.

8.[12] To characterize the physiological premises for the creation by the brain of directing models of the required future, it is essential to note that the physiological aspects of these models and their elements already have been repeatedly described by investigators in their different aspects and under different names such as set, the orienting reaction,[13] neuromuscular tone, anticipatory excitation, and so on. All these notions refer to one common, large group of processes, which precede virtually any action and pave the way for it. Hence, the new understanding of the category of tone[14] that has taken shape deserves special attention.

9. The study of neurophysiological processes in aspects of phylo- and ontogenesis and also of clinical pathology[15] permitted the identification of the two types of nervous and muscular activity designated by me as paleokinetic[16] and neokinetic groups of processes. Neokinetic processes are characterized by high-voltage electronegative potentials, obeying the "all or none" laws, with the rapidly appearing refractory period and with the undamped spread along axons. Paleokinetic processes are low-voltage processes; their changes are not limited to amplitude or duration and allow changes of both signs (anelectrotonic and cathelectrotonic).

In the peripheral neuromuscular apparatus, the paleo-processes (these particular processes are addressed as neuromuscular tone) regulate both the mechanical parameters of the skeletal muscles (unloaded length, modulus of tension) and the electrophysiological parameters of muscles and nerves (the measure of excitability, the speed of the spread along an axon,[17] etc.), preparing the muscle thoroughly for the performance of effector neokinetic commands.

10. At the level of segmental regulating processes within the spinal cord, paleo-regulation is brought about by the matrix-organized reflex rings. However,

at the level of bioelectrical processes in the brain, the paleo- and neo-kinetic types take the shape of wave processes[18] spreading along the neuropile and interneuronal medium and of channel processes limited to the current-isolated membranes of the axons of the white matter of the brain, respectively. Beyond any doubt, the complexly structured wave fronts of the paleo-processes in the brain play the most important role, not only in regulating excitability and inhibiting cortical cells but also in regulating brain rhythms and, possibly, in shaping programs and storing images.

11. Recently revealed patterns of electrophysiological processes of both types, proceeding in the form of complex system combinations in the cortex and subcortical nuclei, allow one to suggest a new interpretation of cortical localization.[19]

The irrefutable demonstration of cortical differentiation based on the micromorphology of the cortical zones and on the diversity of functional disorders depending regularly on the loss of certain cortical areas does not leave room for any antilocalization concepts, at least not in higher mammals. The only open question left is, What is differentially localized in different microscopic zones and microscopic elements within one or another cortical locus?

12. The understanding of every cortical zone (maybe even microscopic ones) as a carrier of a certain operator participating actively in one or another stable function, capable of joining the composition of many semantic programs and block-diagrams in different ways, would, from the modern point of view, provide an answer to this question, which is not clear, even with respect to the primary sensory zones. Corresponding functional interrelationships between the waves and channel processes in each particular zone are structured according to the aims of each operator.

13.[20] At present, the basic problem of primary importance for physiology of activity and even, perhaps, for all biocybernetics is the mathematical problem of displays (models, projections, images, and so forth). While the mathematical interpretation of nonessential variables with their characteristic continuous spread of values is well developed with the help of the theory of probability and mathematical statistics, the key to comprehending the whole range of questions of variables which belong to the essential category undoubtedly lies in the mathematical theory of biological displays, which is at present taking shape. Today it is difficult even to predict which of the essential branches of mathematics will form the abovementioned theory; in any case, obviously, topology, the theory of sets and multivariate ensembles and, maybe, the theory of classes will play an important role.

14. The outlined theory of biological displays faces many other problems in addition to the general, perhaps principal problem of the analysis of models of the future and representing these models or codes.

This theory covers, undoubtedly, all the problems of perception and generalization of images with the applied branch of the creation of efficient percepts. It also covers the theory of structure of generalized commands issued by the higher programming centers to hierarchically subordinated or lower matrices of control. Every motor action directed at solving a problem arising from the model of the future may be considered as a manifestation of this intrabrain model, with the corresponding time delay and with some kind of transformation, depending on peripheral conditions. The enumeration of other questions directly related to the theory described would take too much space.

15.[21] As mentioned above, we have touched only upon a few of the new lines of future developments of neurology and psychophysiology. It has become possible to see tfe mentioned lines and those not discussed in this paper because the biological sciences as a whole have overcome the new borderline and are able to see the wide, unanticipated horizons and perspectives. This borderline, which in the methodological plane meant distinguishing between the old mechanical materialism and the ideas of dialectical materialism[22] that took its place, and which with respect to direct study of living nature corresponded to the powerful technical rearmament and renovation of the mathematical apparatus, means a transfer from the old positions of passive reflexology, which has fulfilled its purpose, to the physiology and biology of activity, to which the future belongs, beyond any doubt.

Notes

[1]This paper was prepared by N.A. Bernstein for a symposium on Cybernetic Aspects of Integrative Brain Activities within the XVIIIth International Congress of Psychology, August 4–11, 1966, Moscow. The original Russian version and an English translation were published in the proceedings of that congress. The translation has been edited for clarity.

[2]The reader is invited to follow Lev Latash's suggestion and to read *initiative* wherever *activity* is written.

[3]Sections 1 and 2 deal with Bernstein's theory of coordination.

[4]Note that Bernstein couched his theory of coordination in a framework of goals of movement and required aspects of the future; that is, coordination is subordinated to initiative.

[5]Sections 3 and 4 introduce the physiology of initiative.

[6]This notion of "projection" already hints at the main argument of the paper (Sections 13 and 14), focusing on the mapping that leads from perception to the selection of an essential variable, and the fanning out of the essential variable into action.

[7]Sections 5 and 6 deal with Bernstein's rejection of the classical concept of reflex arc. The fact that he devoted so much space to this topic derives in part from his clash with the neo-Pavlovians (Bongaardt & Meijer, in press), which had led to his dismissal in 1950. Although he had been reinstated after Stalin's death, Bernstein remained suspect in the eyes of neo-Pavlovians. One should, however, not overestimate the role of Bernstein's personal motives in Sections 5 and 6. His understanding of reflexes as integral actions, determined by their significance for the organism, also introduces the notion of essential variables. In Bernstein's view, meanings and significances are integrated into motor control through the choice of an essential variable.

[8]Bernstein (1965/1988, p. 240) attributed this concept of mosaic to Pavlov.

[9]In Bernstein's theory, spontaneous actions are not "uncaused actions" or "internally caused actions" but actions where in the confrontation of internal meaning with external events, the former outweighs the latter by far. Thus, there exists a continuum between spontaneous action and reflex action (cf. Bernstein, 1965/1988).

[10]Note that the idea of "initiative" is the exact opposite of the conception of the organism as a homeostatic system (Cannon, 1939).

[11]Section 7 emphasizes the ubiquitous nature of essential variables in living organisms.

[12]In Sections 8 through 12, Bernstein related his theory to then-contemporary developments in neurophysiology, and, more importantly, assigned them a place in a new coherent framework. For an overview of developments in the late 60s, one may consult Pribram's *Languages of the Brain* (1971), which also contains several references to Bernstein's work.

[13]Cf. Sokolov (1960).

[14]At the time, tone was regarded as "readiness to respond" (Pribram, 1971, pp. 225-226). Note that Bernstein subsumed the whole readiness literature of the late 60s under his physiology of initiative.

[15]Bernstein (1947/1996, p. 36) described patients with tabes dorsalis. "Blindfold such a patient, lift his arm, and ask him to keep the arm in the same position. The arm will fatigue and slowly and involuntarily lower after a minute or two. The patient will be sure that the arm is still high over the head and will be very much surprised when the blindfold is removed."

[16]In Bernstein's view, the most important paleokinetic function is the regulation of tone.

[17]Note that Bernstein regarded "the speed of the spread [of action potentials] along an axon" as controlled rather than given (cf. Meijer & Bongaardt, 1992).

[18]In the late 60s, slow wave fronts in the brain were seen as a background upon which specific operators exerted modulatory influences that were quick, localized, and channeled (cf. Pribram, 1971).

[19]From 1935 onward, Bernstein occupied himself with localization. His opinion was that there is no one-to-one relationship between specific cortical cells and specific (aspects of) actions, while there are certainly brain areas with specific functions. The cortex appears to be globally localized and locally globalized (cf. Luria, 1976).

[20]Sections 13 and 14 contain the main argument of the paper: The immediate task of neurophysiology is to adopt or develop a mathematical theory of display. Science has to think in terms of "images" (or maps) in order to understand (a) the role of the brain in perception and (b) the funneling of perception into efficient perceptions, which through the choice of an essential variable are linked to (c) generalized motor commands, which then fan out into (d) the lower matrices of control and thus into action.

[21]Section 15 concludes the paper by emphasizing the gap between Bernstein's theory and traditional mechanical materialism.

[22]It is unclear how much of a dedicated communist Bernstein really was. He probably went along with the general enthusiasm of young Soviet intellectuals in the early 20s and with blaming mistakes within the system rather than the nature of the system itself for the atrocities of the 30s. After his rehabilitation, he elaborated on Lenin's philosophy of science (Bernstein, 1957/1967), but it is unclear to what extent that was just a tactical move (Bongaardt, 1996). On the other hand, it must be recognized that the principled rejection of dualism, and later also of mechanicism, helped scientists in the Soviet Union to develop more dynamical, naturalistic theories of life and mind.

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